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Published in:
Optics Letters

Link to article, DOI:
[10.1364/OL.36.001560](https://doi.org/10.1364/OL.36.001560)

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Xu, J., Ding, Y., Peucheret, C., Seoane, J., Mulvad, H. C. H., Galili, M., Xue, W., Mørk, J., & Jeppesen, P. (2011). Demultiplexing of OTDM-DPSK signals based on a single semiconductor optical amplifier and optical filtering. *Optics Letters*, 36(9), 1560-1562. <https://doi.org/10.1364/OL.36.001560>

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Demultiplexing of OTDM-DPSK signals based on a single semiconductor optical amplifier and optical filtering

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Received January 5, 2011; revised March 22, 2011; accepted March 28, 2011;
posted March 31, 2011 (Doc. ID 140681); published April 21, 2011

We propose and demonstrate the use of a single semiconductor optical amplifier (SOA) and optical filtering to time demultiplex tributaries from an optical time division multiplexing-differential phase shift keying (OTDM-DPSK) signal. The scheme takes advantage of the fact that phase variations added to the target channel by cross-phase modulation from the control signal are effectively subtracted in the differential demodulation scheme employed for DPSK signals. Demultiplexing from 80 to 40 Gbit/s is demonstrated with moderate power penalty using an SOA with recovery time twice as long as the bit period at 80 Gbit/s. Large dynamic ranges for the input power and SOA current are experimentally demonstrated. The scheme is expected to be scalable toward higher bit rates. © 2011 Optical Society of America

OCIS codes: 070.4340, 250.5980.

Optical time division multiplexing (OTDM) systems allow generation, transmission, processing, and detection of serial data rates far beyond the speed limit set by electronics [1]. Detection of OTDM signals is usually performed by first extracting the lower speed tributaries from the signal, i.e., demultiplexing from the aggregate rate to the base rate, using high-speed optical switches [2–4]. An ultrafast photonic switch based on an SOA, i.e., an SOA followed by optical filters, has been demonstrated for 640 Gbit/s optical time demultiplexing using an SOA with recovery time larger than 8 ps [4]. The scheme can be traced back to interferometric structures [5,6] and benefits from the fact that the slow recovery process can be effectively equalized by making use of new frequency components of the probe spectrum generated in the SOA [7]. The scheme is also very attractive thanks to its simple structure, improved stability compared to fiber-based solutions, possibility of integration, and low switching power.

The use of phase modulation, such as DPSK, has recently gained favor in OTDM systems thanks to its robustness to transmission impairments [8]. OTDM-DPSK demultiplexing has been recently demonstrated using SOA-based interferometric structures, e.g., from 80 to 10 Gbit/s by placing an SOA (also known as a semiconductor laser amplifier) in a loop mirror [9], and from 640 to 40 Gbit/s by using a symmetric Mach-Zehnder switch incorporating SOAs [10]. The challenge in demultiplexing phase modulated signals in SOAs is that the phase information must be preserved by the switching process. Thanks to the differential demodulation scheme employed for DPSK signals (typically performed in a Mach-Zehnder delay interferometer), any periodic phase variation at the base rate added to the target channel due to cross-phase modulation (XPM) in the SOA can be effectively cancelled out. While for on-off-keying (OOK) signal demultiplexing, interferometric structures have evolved into the much simpler configuration of an SOA followed by offset filtering [7], it remains to be ver-

ified that demultiplexing of OTDM-DPSK signals can also be achieved using this simpler scheme.

In this work, we demonstrate for the first time (to our knowledge) 80 to 40 Gbit/s demultiplexing of return-to-zero (RZ) DPSK signals based on a single SOA assisted by optical filtering. Error-free operation is achieved for the two 40 Gbit/s tributaries with 3.5 and 5 dB power penalty. The $1/e$ recovery time of the SOA is ~ 25 ps, which is twice as long as the bit period at 80 Gbit/s. Thanks to the fact that DPSK signals have identical power in every bit slot, no obvious dependence on the input data pattern length is observed in the experiment.

Figure 1 shows the principle of operation of OTDM-DPSK switching based on a single SOA followed by offset filtering. When a weak probe signal copropagates in an SOA with a strong pulsed pump signal, the probe will be chirped by the pump due to XPM when the pulses are temporally aligned. By placing a frequency discriminating filter that is detuned from the DPSK center wavelength, the DPSK signal is blocked at the output when there is no pump pulse at the input. However, when a pump pulse is present at the input, it will introduce frequency shifts on the DPSK signal due to XPM. If the filter is detuned properly, part of the frequency-shifted DPSK signal will be transmitted through the filter. Since the strong frequency shifts introduced by the ultrafast dynamics of the SOA occur within the pump pulse duration, high-speed switching windows are formed when the

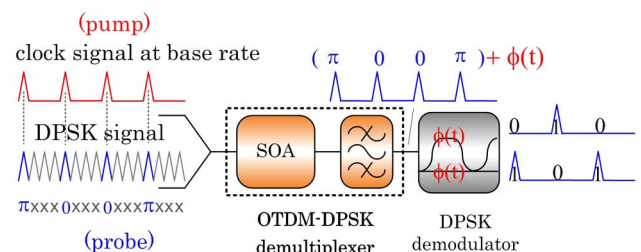


Fig. 1. (Color online) Principle of operation of OTDM-DPSK demultiplexer based on an SOA followed by an optical filter that is detuned from the probe center wavelength.

pump pulses are present. In the demultiplexing case, a clock signal at the base rate (40 GHz, in this experiment) acts as the pump signal, while the high-speed OTDM-DPSK signal acts as the probe signal. Consequently, a switching window is opened when the clock signal is present, resulting in a single OTDM tributary channel being switched to the output. Because of XPM being introduced by the clock signal, a periodic phase variation at the base rate, $\phi(t)$, is added to the phase of the demultiplexed channel. Since this phase variation is identical for every switched bit, its effect will cancel out at the outputs of the 1 bit delay interferometer used for phase-to-intensity conversion of the demultiplexed DPSK signal. It should be noted that since the XPM effect transfers intensity information, but not phase information, to the probe signal, it is very important to use the high-speed OTDM signal as the probe and to carry out offset filtering on the probe spectrum. This is in contrast to [4], where the clock signal was used as the probe signal.

Figure 2 shows the experimental setup for OTDM-DPSK demultiplexing. The details of the transmitter are shown in Fig. 2(a). Two pulse trains at different wavelengths are generated from a common short pulse generator, which consists of two continuous-wave lasers centered at 1546 and 1560 nm, a Mach-Zehnder modulator (MZM) used to carve 50% duty cycle pulses at 40 GHz, and a phase modulator followed by a length of standard single mode fiber (SSMF) for pulse compression [11]. The PM is driven by a 40 GHz radio frequency (RF) signal with $V_{pp} = 3V_{\pi}$, where V_{pp} is the peak-to-peak voltage of the RF signal and V_{π} is the half-wave voltage of the PM. After transmission through a 380 m SSMF, two pulse trains having a full width at half-maximum (FWHM) of 4.7 ps and a repetition rate of 40 GHz are obtained. By dividing the output of the pulse generator into two branches and filtering at different wavelengths using 2 nm bandpass filters (BPFs), the two pulse trains are separated. The pulse train centered at 1560 nm is used as the clock signal, i.e., the pump, in the demultiplexing process. The pulse train centered at 1546 nm is sent into a nonlinear pulse compression stage that further com-

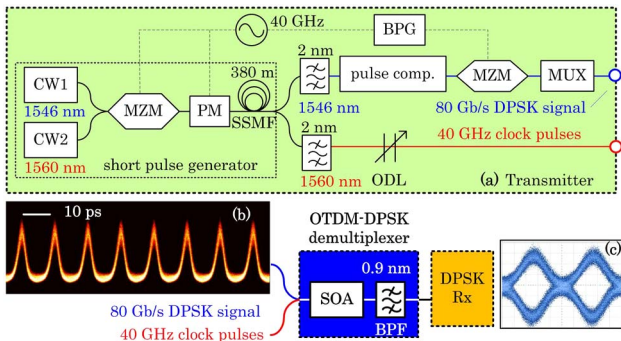


Fig. 2. (Color online) Experimental setup. The OTDM-DPSK demultiplexer is composed of a single SOA followed by a detuned 0.9 nm optical BPF. (a) Details of the OTDM transmitter (b) 80 Gbit/s OTDM-DPSK signal generated by the transmitter (c) typical balanced detected eyes at a BER of 10^{-9} . CW, continuous-wave laser diode; MZM, Mach-Zehnder modulator; PM, phase modulator; SSMF, standard single mode fiber; MUX, optical time division multiplexer; ODL, optical delay line; FBG, fiber Bragg grating.

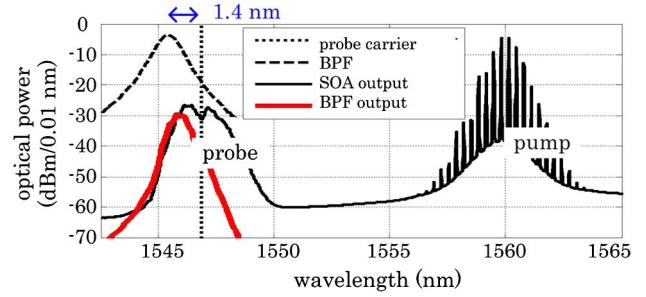


Fig. 3. (Color online) Measured optical spectra at the output of the SOA and after offset filtering of the probe.

presses the signal pulses to 2.5 ps. By feeding the pulse train into another MZM driven by a bit pattern generator, a 40 Gbit/s RZ-DPSK signal is generated. An 80 Gbit/s RZ-DPSK signal, shown in Fig. 2(b), is formed at the output of a 40 to 80 Gbit/s delay line multiplexer (MUX) and used as the probe signal in the demultiplexing process. The OTDM-DPSK demultiplexer consists of an SOA and a 0.9 nm BPF. The BPF is a commercially available optical filter with a Lorentzian-type transfer function (as shown by the dashed curve in Fig. 3). The SOA used in the experiment is designed for nonlinear signal processing. It is biased at 400 mA and exhibits a gain peak at 1560 nm. The typical $1/e$ recovery time is ~ 25 ps, which is twice as much as the bit period of the 80 Gbit/s signal. The input power for the pump (40 GHz clock) and probe (80 Gbit/s RZ-DPSK) signal is 6 dBm and 0 dBm, respectively. The demultiplexed 40 Gbit/s DPSK signal is finally injected into a DPSK receiver consisting of a 1 bit Mach-Zehnder delay interferometer followed by a balanced photodetector with 45 GHz bandwidth. A typical balanced detected eye at a bit error ratio (BER) of 10^{-9} is shown in Fig. 2(c).

The measured optical spectra are shown in Fig. 3. The 80 Gbit/s RZ-DPSK signal and 40 GHz clock signal at the output of the SOA are shown by the solid black curve. The dashed and dotted curves show the transfer function of the 0.9 nm BPF and the probe carrier wavelength, respectively, indicating that the BPF is shifted 1.4 nm to the blue side of the probe center wavelength. The spectrum after the BPF is shown by the thick red curve. Figure 4 shows the measured BER performance of the OTDM-DPSK demultiplexer. The length of the used pseudorandom binary sequence (PRBS) is at first $2^{31} - 1$ (solid symbols). Note that the MUX is not PRBS preserving

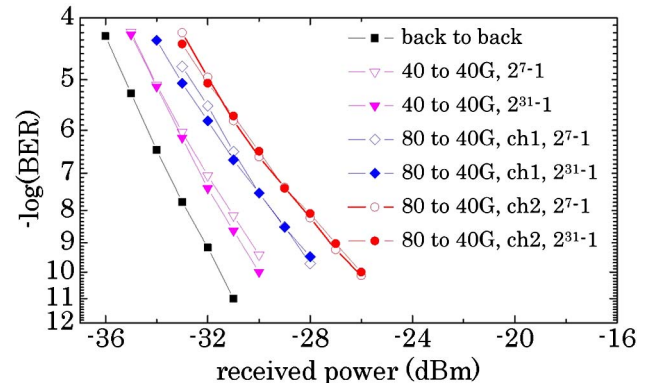


Fig. 4. (Color online) BER performance for 40 Gbit/s switching and for 80 to 40 Gbit/s demultiplexing.

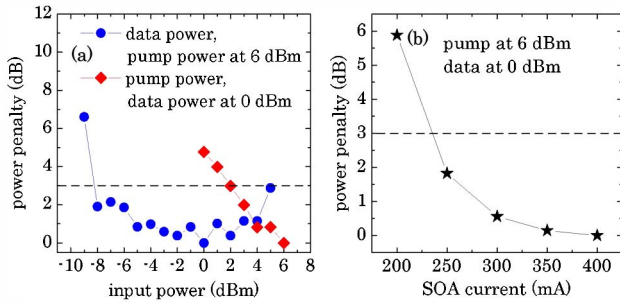


Fig. 5. (Color online) Measurement of the 3 dB input power dynamics as well as operating current dynamics.

at this PRBS length. Error-free performance is achieved for both demultiplexed channels, with 3.5 dB (circle-solid) and 5 dB (diamond-solid) power penalty compared to the back-to-back situation (square). No obvious error floor is observed. The 40 to 40 Gbit/s switching performance was also measured by blocking one path of the MUX. About 2 dB power penalty is observed in this case, indicating up to 3 dB power penalty induced by the cross talk from the neighboring channel. This cross talk is mainly attributed to power leakage of the nontarget channel through the detuned BPF. The cross talk may be improved by creating stronger frequency chirp on the target channel so that the BPF can be tuned further away from the probe center wavelength. No obvious BER variations (<0.5 dB) were observed when using a shorter PRBS of $2^7 - 1$ (open symbols), showing that the scheme is not sensitive to the input data pattern with the aforementioned limitation that the employed multiplexer is not PRBS preserving. This is in accordance with previous observations on SOA-based demultiplexing of OTDM-DPSK signals [9]. The polarization dependence of the scheme is measured to be lower than 0.5 dB, enabled by the use of a polarization insensitive SOA.

The input power and operating current tolerances of the scheme are further characterized. The reference point is chosen as the optimum operation performance that could be achieved in the experiment, i.e., 6 dBm clock (pump) power, 0 dBm data (probe) power, and 400 mA operating current. As shown in Fig. 5(a), when the pump power is fixed at 6 dBm, the input data power can vary from -8 to 5 dBm, while maintaining a power penalty below 3 dB compared to the optimum situation. When the data power is fixed at 0 dBm, the pump power can vary from 2 to 6 dBm with less than 3 dB power penalty. Further increase of the pump power is prohibited in this experiment in order to avoid damaging the SOA. Figure 5(b) shows the operating current dynamics of the scheme. An operating range larger than 150 mA is found for the SOA current, while operating within the 3 dB power penalty limit.

To summarize, we proposed and demonstrated an OTDM-DPSK demultiplexing scheme based on a single SOA assisted by an offset filter. Operation was demonstrated for 80 to 40 Gbit/s demultiplexing with no visible error floor. Up to 3 dB cross talk power penalty is observed and mostly ascribed to the power leakage of the nontarget channel from the detuned BPF. Large input power dynamic range (over 13 dB for the data signal) is achieved. This work demonstrates the suitability of the scheme, already reported for OOK signals, for phase modulated signals. The range of applications of such switches is, therefore, significantly extended for all-optical signal processing of advanced modulation formats. The use of phase modulated signals also alleviates patterning effects of the scheme, which are one of the main drawbacks for SOA-based OOK signal processing [12]. The scheme is expected to be scalable to even higher data rates since the XPM effect can be enhanced by employing shorter pump pulses, which would be necessary when the data symbol rate increases.

This work was supported by Villum Kann Rasmussen Fonden through the Nanophotonics for Terabit Communications (NATEC) center.

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